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A NEW NUMERICAL TECHNIQUE FOR SEARCH OF LOW-ATTENUATED LEAKY WAVES IN CRYSTALS

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ABSTRACT

An efficient numerical technique for the search of orientations in any crystal which support the propagation of low-attenuated leaky waves with Rayleigh-type structure is described. This technique is based on the known relation between the occurrence of pure SAW solutions on leaky wave branch and the so-called "space of simple reflection". The new technique was applied to quartz. As a result, the continuous lines of orientations have been found in which leaky waves propagate with negligible attenuation. One of these lines includes the Rayleigh SAW previously found to exist on leaky wave branch in X-cut of quartz.

I. INTRODUCTION

A variety of specified parameters in modern SAW devices requires new substrate materials with various propagation velocities, high piezoelectric coupling, and low temperature sensitivity. Therefore, in addition to thorough SAW investigations in different crystals, many publications recently appeared on the numerical search for useful leaky surface acoustic waves (LSAW) in piezoelectric crystals. To be of practical importance, any LSAW must be low-attenuated. A numerical procedure which is normally used for the search of low-attenuated leaky waves is a simple scanning of a five-dimensional space defined by the three Euler angles (φ,θ,ψ), velocity V and attenuation coefficient δ of a leaky wave. Such scanning is a rather laborious task, especially if a high accuracy of orientation is required. Therefore, most of the previously found low-attenuated leaky waves propagate in symmetrical orientations, which are characterized by the sagittal plane parallel or normal to the plane of material symmetry.

Obviously, there is a strong need in efficient techniques for "intelligent" search, which could provide improved efficiency of the search procedure due to a reduction of the area under consideration. Such a technique can be developed for each known type of "degenerate" leaky waves with zero attenuation (exceptional bulk waves, simple or composite, and true SAW with Rayleigh-type structure [1]) based on the existence criteria.

The first experience of development an efficient numerical technique helpful in the search for low-attenuated LSAWs was based on the analysis of exceptional bulk waves (see, for example [2]). As a result, the five-dimensional space was reduced to exceptional wave lines which can be easily found in any crystal with the help of bulk wave analysis. Application of this technique to the customary SAW materials explained the existence of low-attenuated leaky waves in 41°-YX cut of $LiNbO_3$ and 36°-YX cut of $LiTaO_3$ and in quartz and lithium tetraborate enabled to find previously unknown quasi-longitudinal type of leaky waves with negligible attenuation.

In this paper similar technique is developed for leaky waves with Rayleigh-type structure and verified for quartz.

2. THEORETICAL BACKGROUND

The true SAW solutions on a leaky wave branch with the structure similar to that of common Rayleigh waves, also called "supersonic" SAWs, are known to exist in some symmetrical orientations. For example, such solutions occur when the sagittal plane is a plane of material symmetry and the shear-horizontally polarized bulk wave has lower velocity than the SAW propagating in the same direction and polarized in the sagittal plane. However, the numerical investigations of leaky waves in some crystals revealed that the occurrence of a true SAW on a leaky wave branch is not necessarily connected with the crystal symmetry [3].

In [4] the general theoretical analysis of supersonic SAWs was performed not assuming the special symmetry. The theory of supersonic SAWs was developed for non-piezoelectric media in which such a wave is two-partial, while in the presence of piezoelectric properties in general it appears to be three-partial. In particular, it was proved that the propagation of such a wave is always accompanied by the so-called "simple reflection" of the uncoupled bulk mode. In this case only one incident and one reflected bulk waves are involved in the reflection problem, as illustrated in Fig.1, while in general there are three reflected waves (non-piezoelectric medium is assumed). The velocity of a supersonic SAW lies in the first "intersonic" interval, i.e. between the limiting (cut-off) velocities of slow quasi-shear and fast quasi-shear bulk waves.

The concept of simple reflection was developed in [5-7]. It was proved that the condition of simple reflection is fulfilled in a two-dimensional subspace of the four-

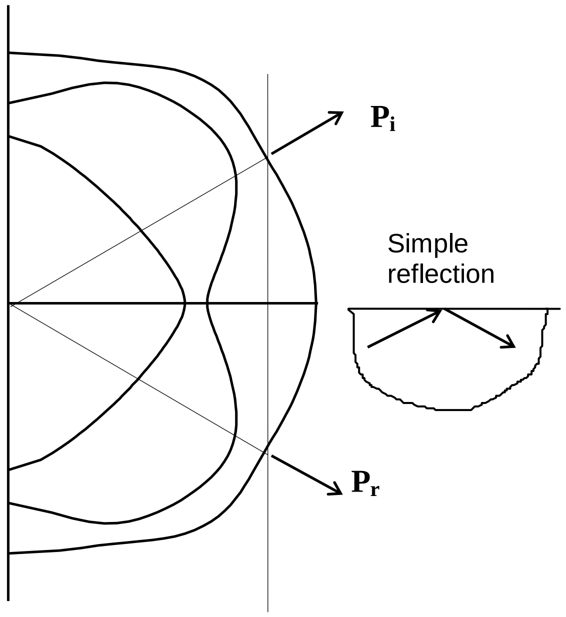

Fig.1. Slowness section in the sagittal plane with two slow quasi-shear bulk waves, incident (Poynting vector $\mathbf{P_i}$*) and reflected (Poynting vector* $\mathbf{P_r}$*) and the scheme illustrating the simple reflection condition with these two waves involved.*

dimensional space defined by the three Euler angles (φ,θ,ψ) and velocity V, and the projections of this subspace onto some symmetric orientations were calculated in crystals with different symmetry.

According to [4], the simple reflection is a necessary though not sufficient condition for the existence of a supersonic SAW. Therefore, a calculation of the simple reflection subspace can be helpful in a search for the non-attenuated true SAW solutions on a leaky wave branch. This idea was successfully implemented in [6,7] and some secluded supersonic SAWs were found in quartz, berlinite and other crystals.

However, a suggestion was made in [4] that in a non-piezoelectric medium the supersonic SAWs must form continuous lines in the four-dimensional space (φ,θ,ψ,V). This assumption was rigorously proved in [8]. The existence criterion was also derived for a branch of two-partial surface waves which is suitable for the search of such waves in “supersonic” and “subsonic” velocity intervals. According to [8], if at least one orientation is definitely known to support the propagation of the supersonic SAW, the entire line can be found using either the derived existence criterion or a numerical technique. In the latter case, the area of search can be reduced to the subspace of simple reflections.

Thus, to find the line of non-attenuated Rayleigh-type solutions among leaky waves one should calculate the subspace of simple reflection and then find the points where this subspace is intersected by leaky wave branches. The effect of piezoelectric properties on the subspace of simple reflections and lines of supersonic SAWs has not been theoretically analyzed. However, one can expect that in a case of a weak piezoelectric crystal (such as quartz) application of the theory developed for non-piezoelectric media can provide sufficiently good approximation.

The same approach was earlier successfully applied to the search of quasibulk leaky waves with negligible attenuation with the help of exceptional wave theory [2]. The piezoelectric effect was taken into account in the calculation of bulk wave characteristics and normal stresses produced by the bulk waves on the surface, by means of using the “stiffened” elastic constants. The electrical boundary conditions were disregarded in the search procedure, though taken into account in the calculation of leaky wave characteristics in the orientations found.

Similarly, the “stiffened” elastic constants can be used for the calculation of velocities, polarization vectors and normal mechanical stresses on the surface for bulk modes which can build a simple reflection solution. Then the normal procedure of leaky wave analysis with the electrical boundary conditions taken into account is applied to the simple reflection subspace found. Low-attenuated leaky waves are expected to propagate in orientations for which the velocities of two solutions - simple reflection and leaky wave - are equal. The example of search for Rayleigh-type waves is given in the next section.

3. NUMERICAL TECHNIQUE AND RESULTS

The numerical technique developed for a search of leaky waves with nearly Rayleigh-type structure and negligible attenuation in a piezoelectric crystal is illustrated by the example of quartz. The line of Rayleigh-type leaky waves is expected to exist for example around the orientation which was found by Farnell [3] and later analyzed by other researchers [7,9]. It is X-cut with the angle between Z-axis and the propagation direction ψ′=153°. This orientation was obtained with the crystallographic axes of quartz chosen to provide a positive value of the elastic modulus C_{14}. With a negative C_{14}, which is more customary for SAW researchers and designers, the same orientation is characterized by ψ′=–153° and the corresponding Euler angles are (90°,90°,117°). For the most widely used set of material constants [10] the Rayleigh-type leaky wave is expected to propagate in the orientation (90°, 90°, 123°).

The velocities of SAWs and leaky waves propagating in X-cut of quartz, Euler angles (90°, 90°, ψ), are plotted in Fig.2 as functions of the angle ψ. The calculations were performed with the material constants from [10]. LSAW branch with propagation velocities exceeding that of the limiting slow quasishear bulk wave exists in the

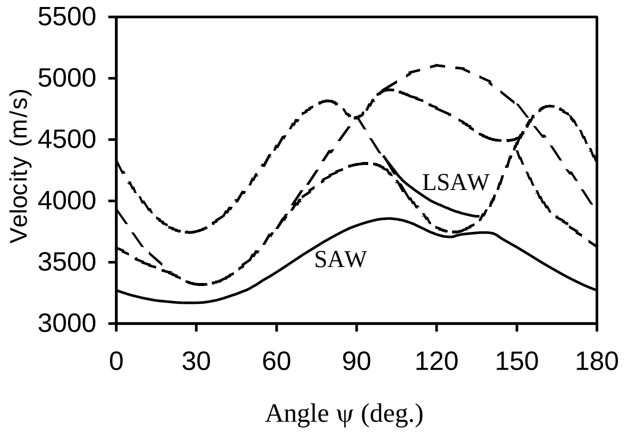

Fig.2. Propagation velocities of SAWs, LSAWs (solid lines) and limiting bulk waves (dashed lines) in X-cut of quartz, Euler angles (90°,90°,ψ), as functions of angle ψ.

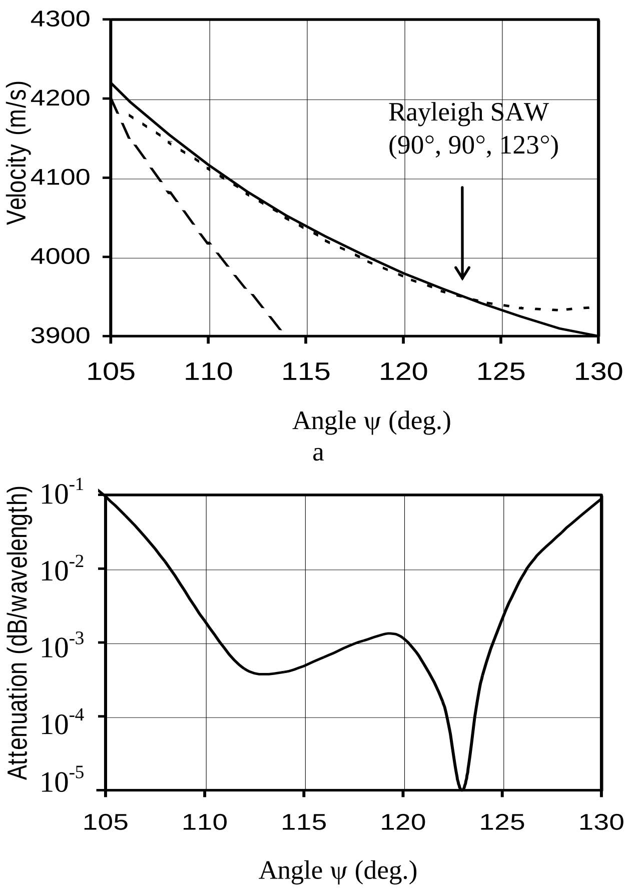

Fig.3. Velocities (a) and attenuation coefficients (b) of leaky waves, propagating in X-cut of quartz, Euler angles (90°,90°,ψ), as functions of angle ψ (solid lines). Dashed and dotted lines show the limiting velocities of bulk waves and the velocities corresponding to simple reflections, respectively.

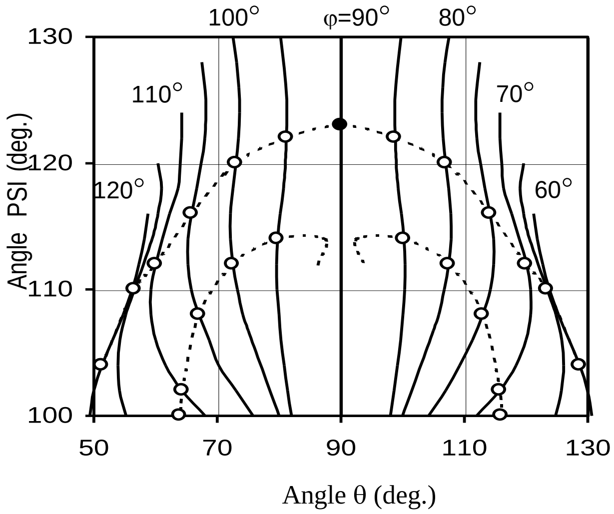

Fig 4. Simple reflection lines (solid lines) corresponding to the fixed values of angle φ in the space of Euler angles (φ,θ,ψ) in quartz. Orientations on these lines which support propagation of low-attenuated leaky waves with Rayleigh-type structure are marked with white circles. Orientation (90°, 90°, 123°) is marked with the black circle.

interval ψ=103…136°. The attenuation coefficient tends to zero for ψ ≈123°.

If the electrical boundary condition is disregarded, the simple reflection subspace can be found from the condition of zero normal stresses produced on the surface by the linear combination of two bulk waves (incident and reflected). These waves have wave vectors in the sagittal plane with the same tangential component (see Fig.1). The subspace of simple reflections defined in this manner is two-dimensional as in the absence of piezoelectric properties. Thus, if one of the three Euler angles is fixed, e.g. φ, a corresponding projection of the simple reflection subspace is a line, e.g. θ(ψ). If two angles are fixed, in general a simple reflection can exist in secluded points. However, if the sagittal plane is parallel or normal to the plane of material symmetry, a line of simple reflections can exist [7].

Fig.3a shows the calculated projection of the simple reflection subspace onto X-cut of quartz. The corresponding line comes very close to the leaky wave branch at the point ψ≈112° and intersects it at the point ψ≈123°. Accordingly, there is a deep minimum in the propagation loss versus angle ψ dependence (Fig.3b) at the first point and vanishing of attenuation coefficient at the second point. Between these two orientations leaky waves have attenuation lower than 0.0013 dB/λ.

The entire subspace of simple reflections can be defined, for example, by the set of "simple reflection lines" θ (φ_n,ψ), where $\varphi_n = \varphi_0 + n*\Delta\varphi$ (n=1,2…N). Such lines were calculated for quartz within crystallographic space defined by the Euler angles (60-120°, 50-130°, 100-130°) and the results are plotted in Fig. 4. The whole picture is symmetrical with respect to the vertical axis φ=90° and one simple reflection line coincides with this axis, thus indicating that the simple reflection condition is fulfilled in the X-cut. The black circle on the vertical axis marks the orientation (90°, 90°, 123°). Other orientations which support the propagation of leaky waves with negligible attenuation were found on the simple reflection lines and in Fig.4 they are marked with white circles. Thus there is a line of leaky waves with Rayleigh-type structure and negligible attenuation (less than 0.001 dB/λ on both free and metallized surfaces). Moreover, the other two lines were found which come very close to X-cut, but do not cross the vertical axis. However, this proximity of the Rayleigh wave lines to X-cut results in the specific behavior of the attenuation coefficients, as shown in Fig.3b.

This numerical technique, in contrast to scanning of the five-dimensional space (φ, θ, ψ, V, δ), provides much higher accuracy of found orientations in which leaky wave turns into Rayleigh SAW. The characteristics of bulk waves are determined through the solution of the Christoffel equation and the normal stresses produced by bulk waves on the surface can be selected real valued, thus making the calculation procedure more simple. The rigorous solution of the boundary problem is performed only along the found lines of simple reflections. The points on these lines at which the difference $\Delta V = V_{LSAW} - V_{SR}$ changes the sign indicate orientations with low-attenuated leaky waves. Here V_{LSAW} and V_{SR} are the velocities of a leaky wave and a simple reflection solution, respectively.

CONCLUSIONS

The idea of using the space of simple reflections for a search of secluded Rayleigh-type solutions on a leaky wave branch, previously discussed in theoretical works and applied to some symmetric orientations, has been developed to provide an efficient numerical technique for the accurate calculation of continuous lines of Rayleigh-type waves in crystals. Due to implementing of this technique to quartz, the lines of earlier unknown non-symmetric orientations, in which leaky waves are expected to propagate with negligible attenuation, have been found. In these orientations leaky waves are expected to propagate with attenuation less than 001dB/λ on both free and metallized surfaces.

ACKNOWLEDGMENT

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